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Materials Report, 77-A

FATIGUE CRACK INITIATION PROPERTIES OF WELDED  
AND STRESS RELIEVED HY 130 STEEL

I. P. Nikiforuk B. F. Peters

December 1977

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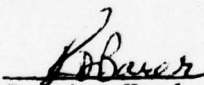
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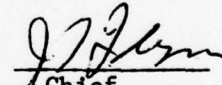
FATIGUE CRACK INITIATION PROPERTIES OF  
WELDED AND STRESS RELIEVED HY130 STEEL

BY

T.P. Nikiforuk and B.F. Peters

December 1977

  
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A B S T R A C T

Fatigue initiation studies were performed on a potential hydrofoil material, HY130 steel, using a Tatnal-Krause type fatigue testing machine.

The welded HY130 steel shows fatigue endurance properties of 480 MPa (70 Ksi) when in the ground and polished condition, the condition which would be present in the highly stressed areas of a foil. In the as-welded condition, the material shows an endurance limit of 240 MPa (35 Ksi) at a stress ratio of  $R = +\frac{1}{2}$ .

Local high residual tensile stresses, due to welding, have little, if any, effect on the fatigue initiation properties of the welded HY130 steel specimens.

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FATIGUE CRACK INITIATION PROPERTIES OF  
WELDED AND STRESS RELIEVED HY130 STEEL

by

T. P. Nikiforuk and B. F. Peters

INTRODUCTION

The suitability of weldable high strength alloys for advanced surface ships has received considerable attention in recent years.<sup>1,2</sup> Some of these alloys have even been used in prototype ships with some success. One weldable high strength low alloy steel, HY130, has been recommended as suitable for a 90 knot hydrofoil.<sup>3</sup> The advantages of this material are:

- 1) It has excellent fracture toughness, having a fracture toughness parameter,  $K_{IC}$ , in excess of  $132 \text{ MNm}^{-3/2}$  ( $120 \text{ Ksi } \sqrt{\text{in}}$ ).<sup>4</sup>
- 2) It is not subject to environmental crack initiation in plate or welded material.<sup>4,5</sup>
- 3) It has very good environmental cracking resistance, having a  $K_{ISCC}$  parameter in excess of  $110 \text{ MNm}^{-3/2}$  ( $100 \text{ Ksi } \sqrt{\text{in}}$ ) for parent material and  $88 \text{ MNm}^{-3/2}$  ( $80 \text{ Ksi } \sqrt{\text{in}}$ ) for welded material, as well as, a  $K_{IHAC}$  parameter in excess of  $93.5 \text{ MNm}^{-3/2}$  ( $85 \text{ Ksi } \sqrt{\text{in}}$ ) for parent material and  $55 \text{ MNm}^{-3/2}$  ( $50 \text{ Ksi } \sqrt{\text{in}}$ ) for welded material.<sup>4</sup>
- 4) The steel is readily available and poses no fabrication problems. It does not require a post fabrication heat treatment for strength requirements.

Under fatigue conditions, high strength materials are known to be particularly sensitive to notches and other stress raisers.<sup>6</sup> Also, because of the high service stresses associated with high strength material the problem of notch sensitivity requires more attention in the high strength steels than for low strength materials; that is, relatively small defects will initiate fatigue cracks. Accordingly, much of the international work on HY130 has centred on fatigue crack growth rates,<sup>7</sup> assuming cracking will always occur in the life of any ship.<sup>8</sup> This work however, has been conducted on the fatigue crack initiation properties of welded HY130 steel.

Residual stresses are known to affect the fatigue properties of materials.<sup>9</sup> Compressive stresses enhance fatigue performance (i.e. shot peening) and tensile stresses degrade fatigue performance. High residual stresses are known to be present in and around HY130 weldments.<sup>10,11,12</sup> In structures, the stresses are of two types:

- 1) local residual stresses close to or in the welds, some likely near the yield point,<sup>10</sup>
- 2) longer range residual stresses due to locked in fabrication stresses<sup>9</sup> (which in fatigue have the effect of changing the R-ratio\*).

Because stress relief heat treatments are being considered for welded HY130 steel, studies have been conducted on the fracture toughness properties<sup>15</sup> of stress relieved HY130 weldments. These studies have indicated that a reduction in toughness was experienced by the HY130 - E12018 weldments when heat treated at 621°C (1150°F) for 2 hours and furnace cooled. It is possible that this heat treatment might also affect fatigue properties.

Accordingly, this present study was conducted to:

- 1) review the fatigue initiation properties of welded HY130 steel, and
- 2) evaluate the effect of residual stress and stress relief heat treatment on the fatigue initiation properties.

\*The R-ratio in fatigue is the ratio of the minimum stress to the maximum stress.

# EXPERIMENTAL

Four series of fatigue tests were performed:

- 1) Parent material, fine ground and polished,  $R = -1$ 
  - (a) from "as received" material
  - (b) from "stress relieved" material
- 2) Mill-finished parent material (ground on one side),  $R = -1$ 
  - (a) from "as received" material
  - (b) from "stress relieved" material
- 3) HY130 welded with MIL-140S wire, fine ground and polished,  $R = -1$ 
  - (a) from "as welded" material, with weld running across the specimen
  - (b) from "stress relieved" material, as above
- 4) Mill-finished material welded with E12018 rod, and the weld bead left proud,  $R = -1$ ,  $R = 0$ , and  $R = \frac{1}{2}$ .
  - (a) from "as welded" material with weld running across the specimen as in Figure 1.
  - (b) from "stress relieved" material, as above.

The parent material was Air Melt Vacuum Degassed (AMVD) HY130 steel. Table 1 gives the compositions of the parent material and the weldments.

TABLE I

Compositions of HY130 and Weldments (in weight percent)

|                    | <u>C</u> | <u>Ni</u> | <u>Mn</u> | <u>Cr</u> | <u>Mo</u> | <u>V</u> | <u>Si</u> | <u>S</u> |
|--------------------|----------|-----------|-----------|-----------|-----------|----------|-----------|----------|
| AMVD plate         | 0.1      | 5.3       | 0.78      | 0.59      | 0.49      | 0.06     | 0.3       | 0.012    |
| E12018 weld rod    |          | 2.3       | 1.6       | 0.74      | 0.37      |          |           |          |
| MIL-140S Mig. weld |          | 2.1       | 1.9       | 0.88      | 0.54      |          |           |          |

The MIG welding involved the use of Argon - 2% oxygen shielding gas and 0.89 mm (0.035") filler wire (MIL-140S) stored at 30°C (85°F). The parent metal plate was preheated at 120°C (250°F) and welded with multiple passes (all weave) at 28V and 225A.

The E12018 weldments involved the use of 3.2 mm (0.125") stick electrodes for the root passes and 4.1 mm (0.16") electrodes for the remainder. Electrodes were stored at 177°C (350°F) for 48 hours prior to reversed polarity welding at a current of 170A.

The flat specimens were all similar in shape to that shown in Figure 1. Specimens for Series 1 to 3 were all cut from 12.7 mm (0.5 in.) plate and ground to final dimensions approximately 3.2 mm (0.125 in.) thick. Prior to testing, all the ground surfaces were hand polished longitudinally to ensure that small stress raisers were removed.

The fatigue specimens were cycled in a Tatnal-Krause type fatigue testing machine (Figure 2) at a cyclic speed of approximately 1200 CPM. Normally, specimens were cycled to failure or to  $10^7$  cycles.

Heat treatments for series 1-3 were performed in a tube furnace, holding the specimens at 621°C (1150°F) for 2 hours while purging with preheated argon. Specimens for series 4 were placed in heat treating bags and held for 2 hours at 621°C (1150°F) in a Dyna Trol box furnace. All stress relieved specimens were furnace cooled.

Due to limitations in supply, normally only one specimen was tested at each stress level for a given series.

## RESULTS

The results of the fatigue tests are presented in Figures 3-6, and summarized in Table II.

TABLE II

Summary of Fatigue Tests.

| <u>Series</u> | <u>Description</u>  | <u>R Ratio</u> | <u>Approximate Endurance Limit</u> | <u>Remarks</u>             |
|---------------|---|----------------|------------------------------------|----------------------------|
| 1(a)          | AMVD G&P (i)  | -1             | 515-550 MPa (75-80 Ksi)            |                            |
| (b)           | as above SR (ii)  | -1             | 515-550 MPa (75-80 Ksi)            |                            |
| 2(a)          | Mill-finished surface   | -1             | 310-345 MPa (45-50 Ksi)            |                            |
| (b)           | as above SR   | -1             | 310-380 MPa (45-55 Ksi)            |                            |
| 3(a)          | MIG Welded G&P (transverse weld)  | -1             | 480 MPa (70 Ksi)                   | Failed well away from weld |
| (b)           | as above SR   | -1             | 380-415 MPa (55-60 Ksi)            | Failed in weld             |
| 4(a)          | E12018 weld   | -1             | 140 MPa (20 Ksi)                   |                            |
| (b)           | as above SR   | -1             | 140 MPa (20 Ksi)                   |                            |
| (c)           | E12018 weld   | 0              | 170 MPa (25 Ksi)                   |                            |
| (d)           | as above SR   | 0              | 170 MPa (25 Ksi)                   |                            |
| (e)           | E12018 weld   | +1/2           | 240 MPa (35 Ksi)                   |                            |
| (i)           | G&P, Ground and Polished  |                |                                    |                            |
| (ii)          | SR, Stress relieved at 621°C (1150°F) 2 hours, followed by furnace cooling. |                |                                    |                            |

The Series 1 specimens indicated (Figure 3) that HY130 had, in the machined and ground condition, an R = -1 endurance limit of approximately 515-550 MPa (75-80 Ksi). It would appear that the stress-relief heat treatment had no significant effect on the fatigue properties of the parent plate.

The mill-finished plate, with its rough "pebbled" surface, Series 2 and Figure 4, had a much lower endurance limit; that is, approximately 310 MPa (45 Ksi) at  $R = -1$ . Here again, the stress relief heat treatment had no significant effect. It was observed, with these specimens, that more than one crack would initiate on the rough mill-finished plate, as shown in Figure 7.

The welded (MIG) ground and polished specimens, Series 3(a) and Figure 5, showed an endurance limit at  $R = -1$  of approximately 480 MPa (70 Ksi). It is noteworthy that all but one of these specimens failed in the same place in the parent plate, well away from the weld and heat affected zone. The stress relieved specimens tended to fail in the weld and the endurance limit appears to have been reduced to approximately 415 MPa (60 Ksi) by the heat treatment. The tendency for the as-welded specimens to fail outside the weld zone (region of highest residual stress) was quite distinct.

One of the fatigue specimens from Series 3(a) was analyzed for residual stresses at the University of B.C., using x-ray diffraction techniques. The results for the specimen shown in Figure 8 before and after fatigue testing at a stress of 415 MPa (60 Ksi) for  $7.6 \times 10^6$  cycles, are outlined in Table IIIA. These specimens had been ground to 3.2 mm thick with the result that the residual stresses were significantly reduced from the as-welded plate. DREP residual stress results based on strain gauge work on as-welded E12018 weldments<sup>12</sup> are summarized in Table IIIB.

TABLE IIIA

| <u>Position</u> | <u>Stress Prior to Fatigue</u> | <u>After Fatigue</u> |
|-----------------|--------------------------------|----------------------|
|                 | MPa (Ksi)                      | MPa (Ksi)            |
| 0               | 5.5 (0.8) Ten.                 | 11.0 (1.6) Ten.      |
| 1               | 5.5 (0.8) Ten.                 | 11.0 (1.6) Ten.      |
| 2               | 16.5 (2.4) Comp.               | 16.5 (2.4) Ten.      |
| 3 (in HAZ)      | 60.8 (8.8) Ten.                | 66.2 (9.6) Ten.      |
| 4 (in Weld)     | 5.5 (0.8) Comp.                | 38.6 (5.6) Ten.      |
| 5 (in HAZ)      | 71.7 (10.4) Ten.               | 71.7 (10.4) Ten.     |
| 6               | 16.5 (2.4) Comp.               | 16.5 (2.4) Ten.      |

TABLE IIIB

| <u>Position</u>        | <u>Residual Stress</u> |
|------------------------|------------------------|
|                        | MPa (Ksi)              |
| in weld (longitudinal) | 228 (33) Comp.         |
| in weld (transverse)   | 248 (36) Comp.         |
| HAZ (longitudinal)     | 276 (40) Ten.          |

The hardnesses of the fatigue specimens were also evaluated before and after stress relief heat treatment, as shown in Figure 9. Hardness tests indicated that the heat affected zone was significantly stronger than the parent plate and weld. Stress relief heat treatment lowered the overall hardness of the specimen but the HAZ remained stronger.

The welded (E12018) 6.4 mm (0.25 in.) specimens, Series 4 and Figure 6, showed similar fatigue properties in the as-welded and stress relieved conditions when tested at all R values. The fatigue endurance limit varied with R values: 140 MPa (20 Ksi) at  $R = -1$ , 170 MPa (25 Ksi) at  $R = 0$ , and 240 MPa (35 Ksi) at  $R = \frac{1}{2}$ . Failure in all cases occurred at the notch formed by the weld bead and the parent plate, as shown in Figures 10 and 11.

Fatigue fractures produced in all four series were also evaluated using electron fractography. There was no distinct difference in the fracture appearance of parent material before and after stress relief heat treatment. A typical area of fracture is shown in Figure 12. The fatigue striation indications are not pronounced for this  $R = -1$  specimen. Fatigue fractures in the weldments (Series 3) were not as flat. (Figure 13). However, indications of striations were, again, not very pronounced.

Considering the Series 4 fatigue specimens, where comparisons could be made for the heat affected structure (Figure 11), no differences were noted between material in the as-welded and stress relieved conditions. However, there were distinct differences between specimens that had been stressed under  $R = -1$  and  $R = 0$  conditions: those stressed in straight tension ( $R = 0$ ) showed very distinct striations, as in Figure 14, compared to those tested under both tension and compression conditions ( $R = -1$ ), as in Figure 15.

## DISCUSSION

The foregoing results indicate that the fatigue properties of the welded HY130 steel are similar to those of other high strength steels.<sup>13</sup> As Figure 16 shows, other high strength construction steels with tensile strengths of 980 MPa (142 Ksi) also have fatigue strengths of approximately 550 MPa (80 Ksi) when ground and polished. Similarly, for other surface conditions, the HY130 steel has fatigue properties which compare to other high strength steels.

It has been proposed that stress relief heat treatment, to remove<sup>10,11,12</sup> high residual tensile stresses known to exist in the weld regions, should improve the fatigue endurance limit. However, stress relief heat treatment of the ground and polished welded HY130 has resulted in a lowering of the endurance limit. As well, failure of the welded material occurred in the parent material (around position 1 in Figure 8) where the residual stress is approximately 5.5 MPa (800 psi) tension, (see Table IIIA) and not in the heat affected zone where the residual tensile stresses are much higher or in the weld where small defects would be more likely. After heat treatment the fatigue failures occurred in the weld, and at lower stresses.

These results from the ground and polished welded specimens may be explained as follows.

- 1) The high residual tensile stresses in the heat affected zone of the welded specimens did not deleteriously affect the fatigue properties because the welding process, as well as producing the residual stresses, also resulted in strengthening this H.A.Z. material as shown in Figure 9. Specifically, the 1200 MPa (175 Ksi) UTS heat affected zone material with its high residual tensile stresses was less subject to fatigue initiation than the 1070 MPa (155 Ksi) UTS parent material, because it is stronger.
- 2) The high residual compressive stresses in the weldments did, apparently, improve the fatigue properties of this material. Otherwise, why would failure take place in the 1070 MPa (155 Ksi) UTS parent material and not in the 1035 MPa (150 Ksi) UTS weld material with its inhomogeneities and greater likelihood of small defects.

Also, during fatigue pre-cracking of notched fracture toughness specimens for DREP fracture toughness tests, it was observed that as-welded material required significantly higher stresses to produce fatigue cracks than either parent material or stress-relieved weld material. Obviously the high residual compressive stresses in the weldments have significantly enhanced the fatigue crack initiation properties of the weldments.

Considering the stress relieved material, the decrease in fatigue properties is associated with the removal of residual compressive stresses. With the beneficial residual compressive stresses removed, the welds, being the weakest material, become the site for fatigue crack initiation.

When comparing the as-welded and the stress relieved weld properties, one wonders whether the reduction in fatigue endurance limit from better than 480 MPa (70 Ksi) to 380 MPa (55 Ksi) can be attributed to the removal of residual compressive stresses and the decrease in hardness alone. Charpy V-notch results indicated that the 621°C (1150°F) stress relief heat treatment<sup>15</sup> decreased the impact properties of E12018 weldments significantly. The fatigue results may support the position that the temper embrittlement in these particular weldments also deleteriously affected the fatigue<sup>14</sup> initiation properties. This finding would be contrary to the literature.

Based on the limited data, the unwelded mill-finished material (Series 2, Figure 4) showed no significant change in fatigue properties when stress<sup>10,11</sup> relieved. It is known that the mill-finished material has large surface compressive residual stresses, stresses that should improve the endurance limit of the material. However, the stress relief which removed these stresses did not lower the endurance limit of the material, indicating that the surface roughness effect is the more dominant factor.

The residual stress study on the electropolished specimen (Figure 8) stressed at 415 MPa (60 Ksi) for  $7.6 \times 10^6$  cycles, indicated that fatiguing did not result in a stress relief. This is consistent with the results of others<sup>9</sup> for specimens evaluated at stresses near the fatigue limit.

The question of the effects of possible residual stresses due to grinding in the Series 1-3 fatigue specimens was also considered in this study. It is noteworthy that, in Series 1, the ground material produced marginally better fatigue results than the ground and stress relieved material. Any deleterious residual stress effects due to grinding were,

apparently, very small.

#### DESIGN CONSIDERATIONS

Before extrapolating these fatigue results to real structures such as hydrofoil foils, it should be noted that the above results were obtained from specimens subject to bending stresses. In these specimens the maximum stresses are at the surface (where small defects can be detected with NDT - and none were present in the specimens evaluated). In actual foils, the fatigue loading will be such that the whole weld will be subjected to the maximum stresses. Accordingly, subsurface flaws which are less readily detected with NDT could cause the actual welds to show poorer fatigue initiation properties than the DREP fatigue specimens indicated. The need for detailed and careful NDT on commercially produced welds is, clearly, of utmost importance.

When considering the design of high performance structures, such as hydrofoil foils, made from HY130, it is apparent that the highly stressed welds should be ground flush so that an endurance limit of 480 MPa (70 Ksi) at  $R = -1$  can be considered. The closing welds in a foil, where machining is not possible [with their endurance limit of 240 MPa (35 Ksi) at  $R = +\frac{1}{2}$ ], should be designed into areas of the foil subject to compressive stresses.

The value of any stress-relief heat treatments in a welded hydrofoil foil made from HY130 is not evident. The above results indicate that the high local residual weld stresses do not show any detrimental effects on fatigue initiation of HY130 steel weldments. Indeed, local residual compressive stresses in the welds (where defects are more likely) could be beneficial. Also, preliminary work at DREP has indicated that long range stresses in fabricated structures of HY130 have varied from 21-42 MPa (3-6 Ksi). The softening effects of stress relief heat treating at 621°C (1150°F) for 2 hours followed by furnace cooling has a much greater deleterious effect on fatigue than would the 42 MPa (6 Ksi) stress. While stress relief heat treating at 540°C (1000°F) for 6 hours would reduce the softening, it is not apparent that such a heat treatment would have any value.

It might be noted at this point, that the high residual stresses in the HMCS BRAS D'OR hydrofoil foil caused stress corrosion cracking and

hydrogen cracking.<sup>16</sup> HY130 steel has a very high resistance to cracking by these mechanisms and, accordingly, residual stress relief heat treatments are not necessary to alleviate these problems in HY130 steel structures.

The above results, based on small laboratory specimens, indicate that a hydrofoil foil built from HY130 steel;

- 1) needs to be carefully designed to ensure that the high fatigue properties of HY130 can be utilized;
- 2) needs to be meticulously evaluated by NDT after welding, using every technique available (AE, radiography, ultrasonics) to ensure sound welds;
- 3) needs no residual stress relief heat treatments.

#### CONCLUSIONS

1. Welded HY130 steel shows similar fatigue properties to those of other high strength steels.
2. For completely reversed loading ( $R = -1$ ), ground and polished samples of welded HY130 have a fatigue endurance limit of 480 MPa (70 Ksi), only slightly lower than the 550 MPa (80 Ksi) endurance limit of the parent plate.
3. The fatigue endurance limit of as-welded HY130 with the weld bead proud (notch effect) varies from 140 MPa (20 Ksi) at  $R = -1$  to 240 MPa (35 Ksi) at  $R = \frac{1}{2}$ .
4. Local high residual tensile welding stresses, due to welding, have relatively little if any, effect on the fatigue initiation properties of welded HY130 steel specimens.

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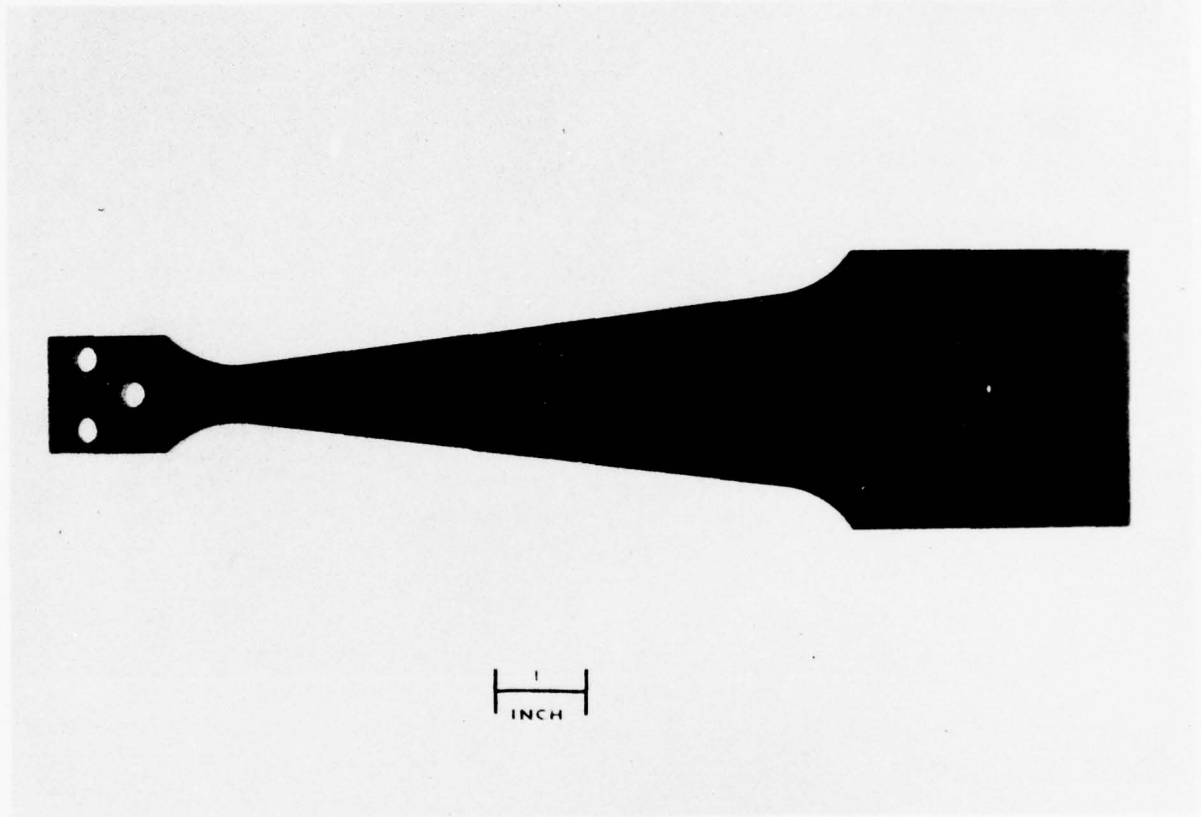


FIGURE 1: 6.4 mm(.25 in) thick HY130 plate fatigue specimen with E12018 stick weldment (for Series 4a to 4e)

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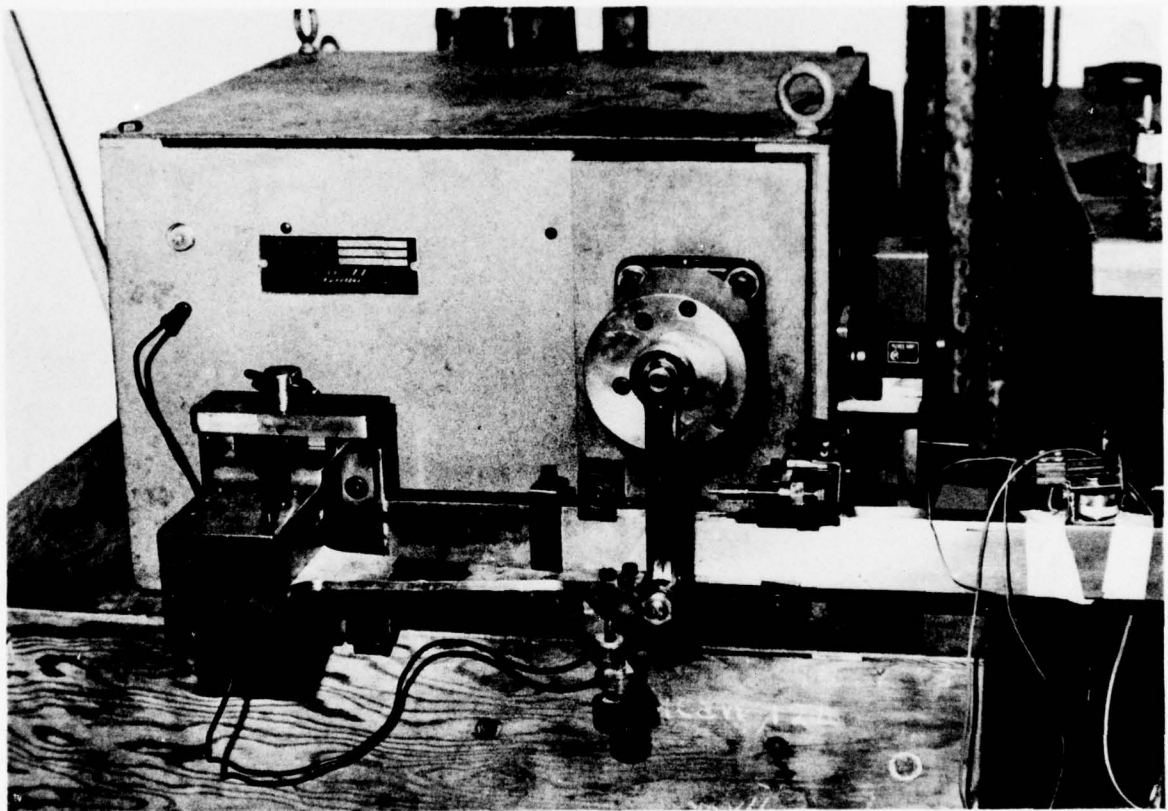


FIGURE 2: Fatigue specimen in DREP Tatnal-Krause type fatigue machine.

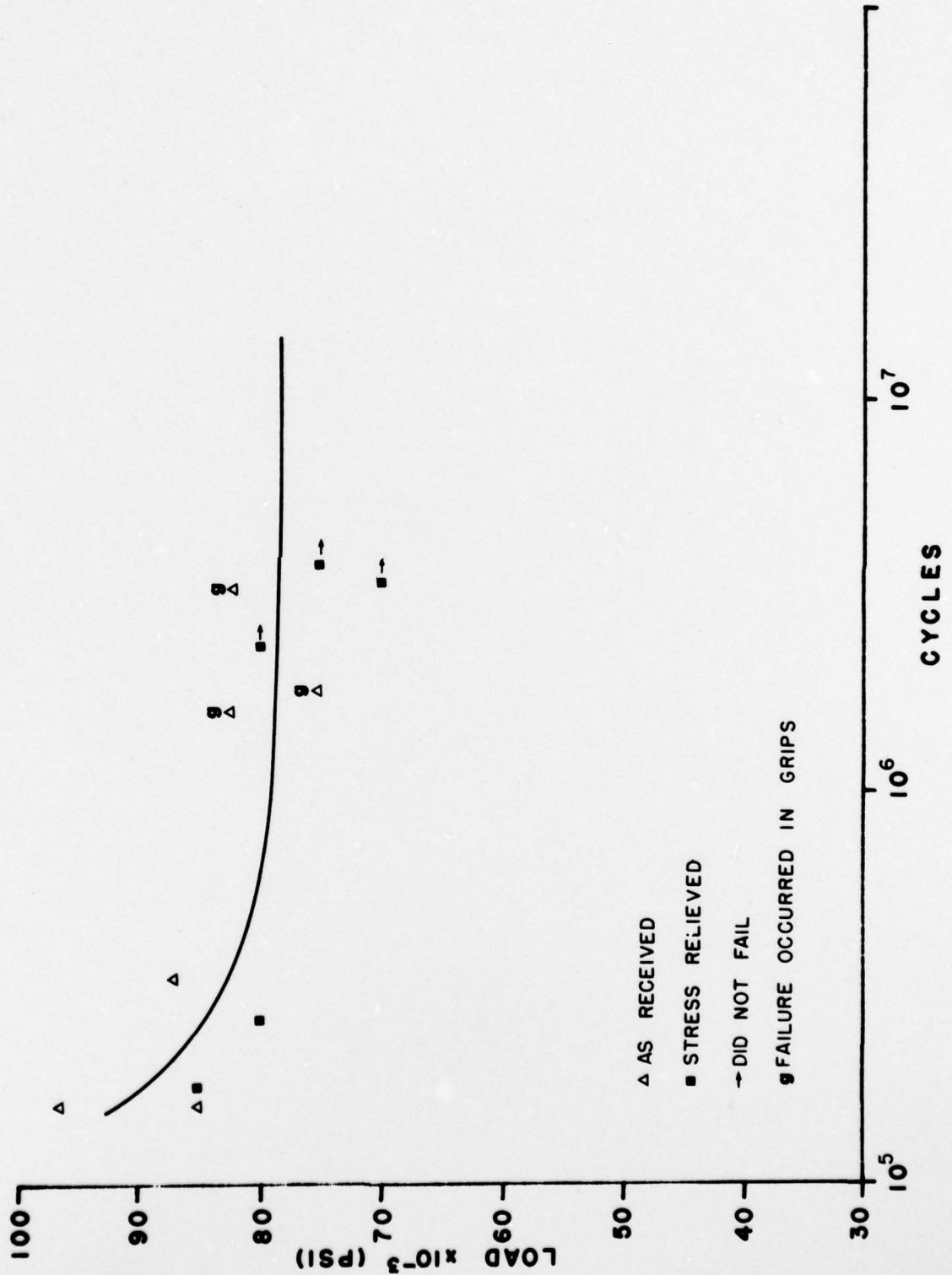


FIGURE 3: S-N Curve for AMVD HY130 plate. Machined and ground (Series 1a and 1b).

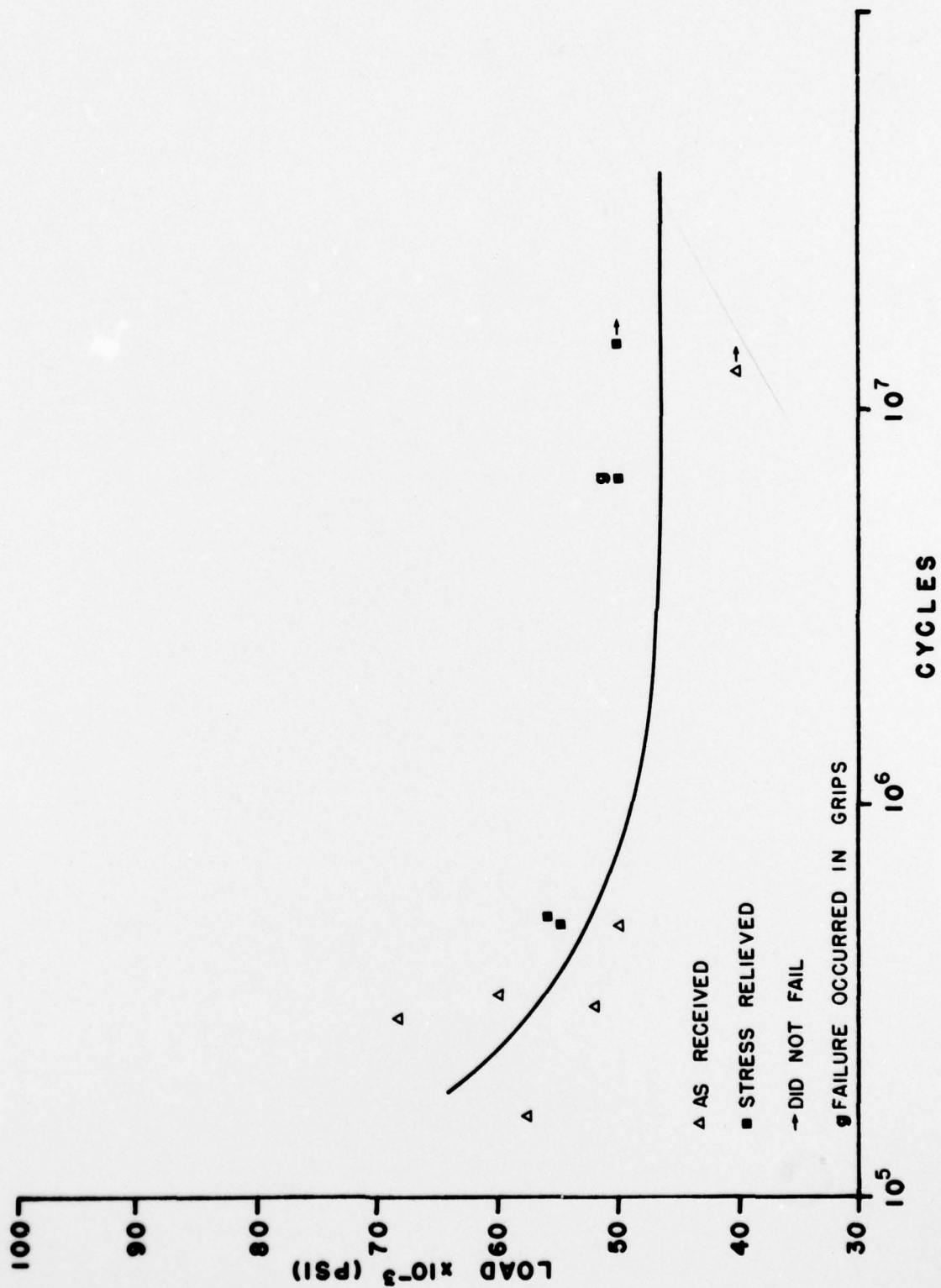


FIGURE 4: S-N Curve for AMVD HY130 plate "as-rolled" (mill finish, Series 2a and 2b).

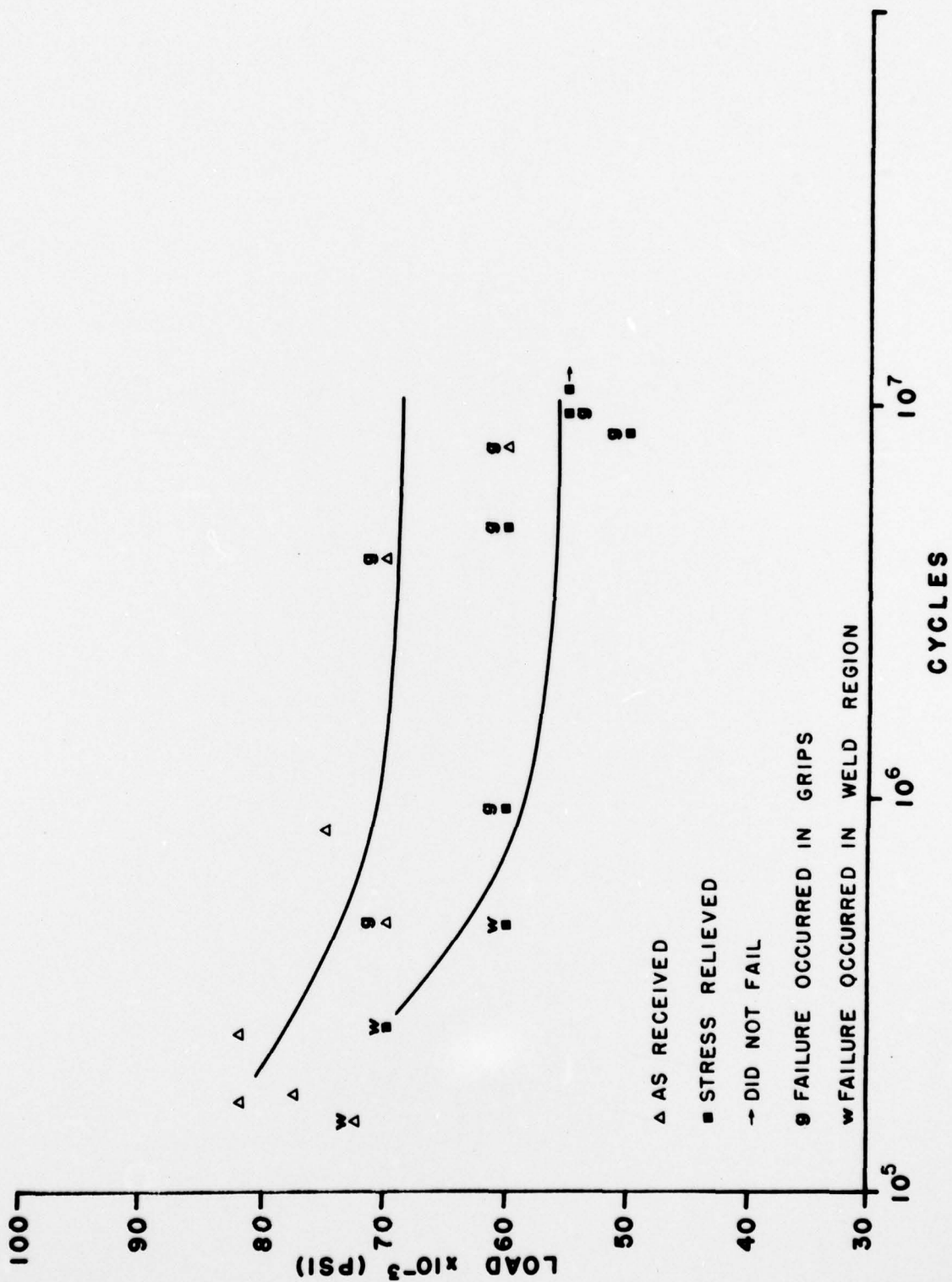


FIGURE 5: S-N Curve for AMVD HY130 plate, 140 Mig welded. Ground and polished. (Series 3a and 3b)

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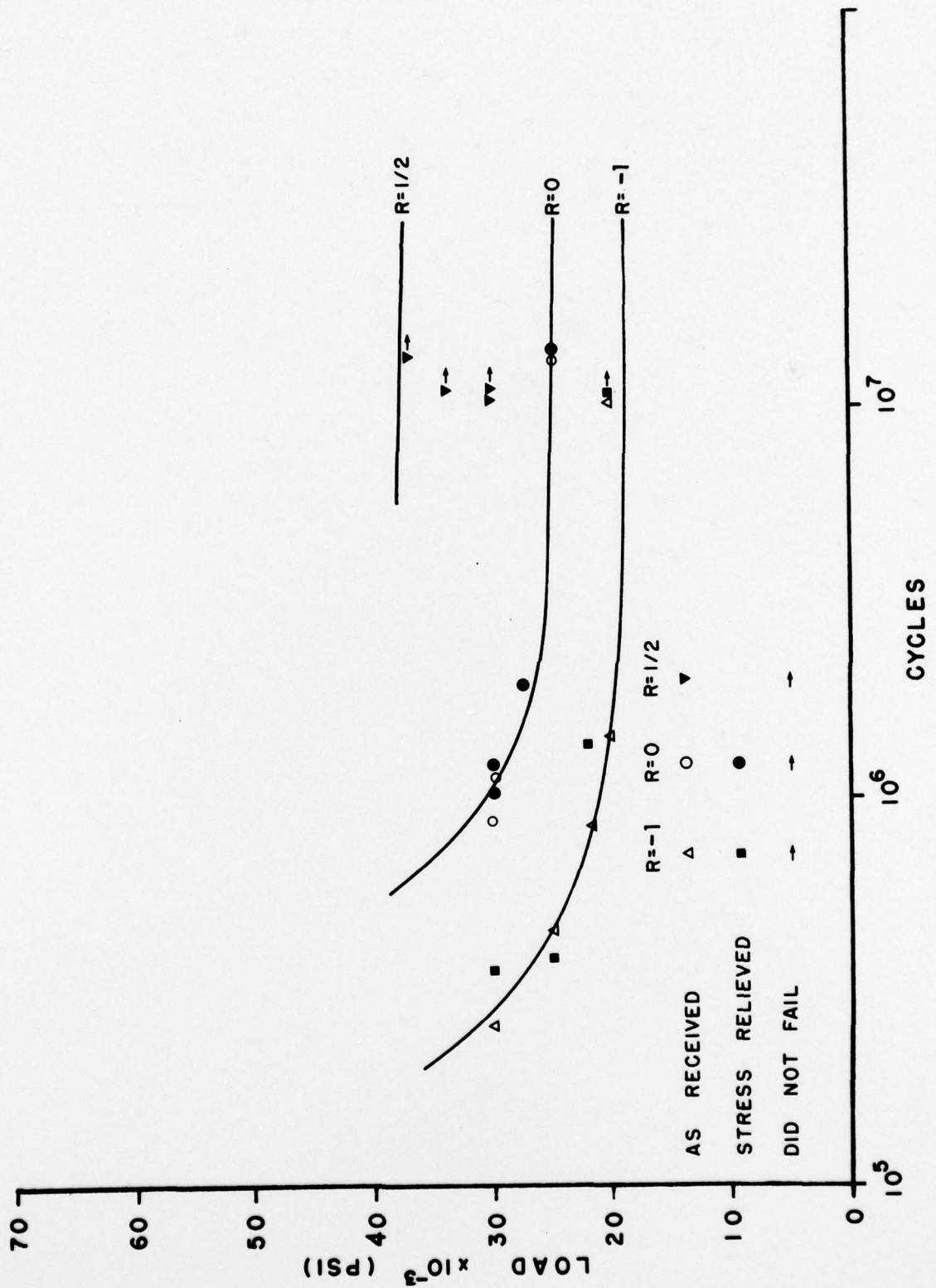


FIGURE 6: S-N Curve for (6.4 mm) AMVD HY130 plate, E12018 welded, "as-welded" (Series 4a to 4e)

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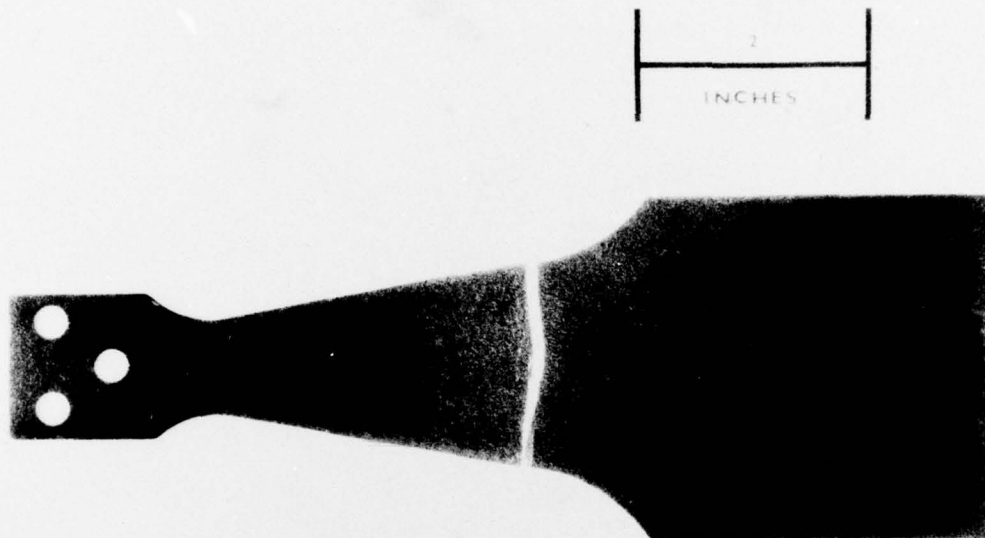


FIGURE 7: Mill finished fatigue specimen, from Series 2a and 2b, showing more than one crack initiating.

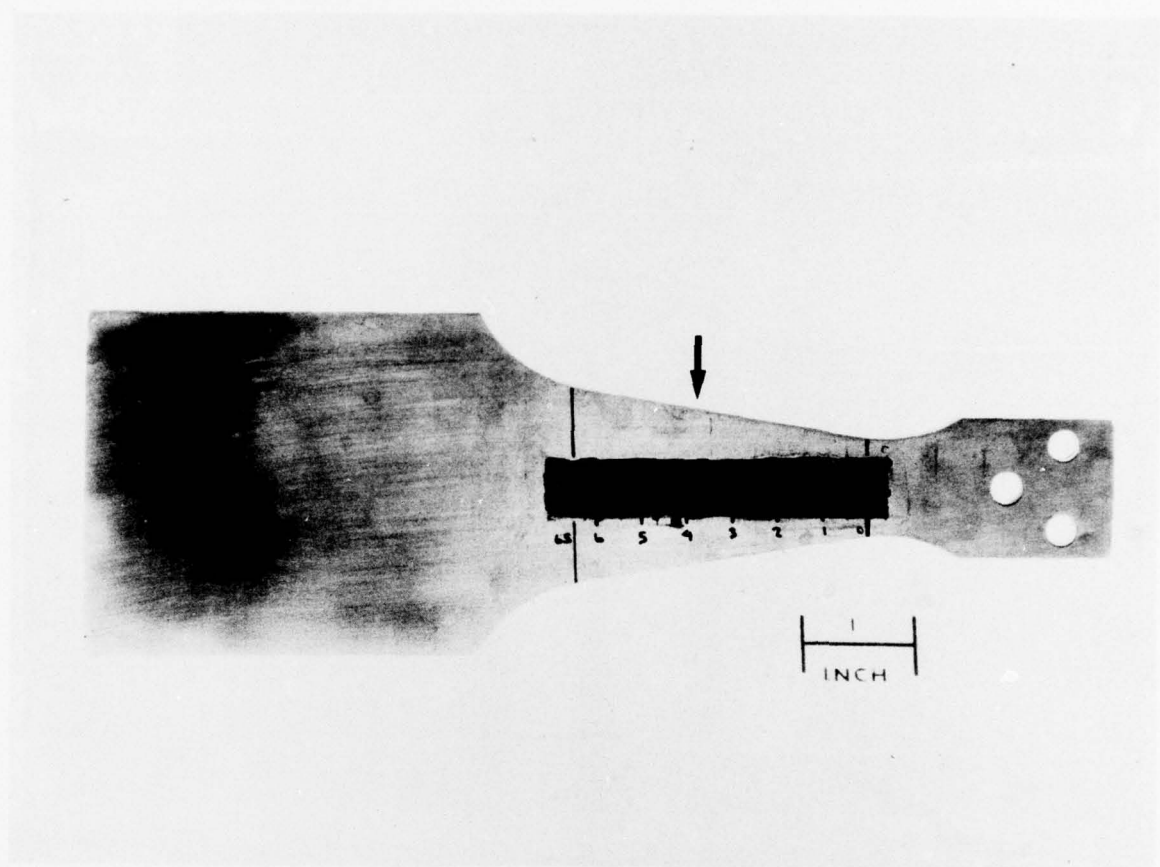


FIGURE 8: Mig-welded specimen from Series 3a, electropolished to evaluate residual stresses (see TABLE IIIA). The arrow marks the weld.

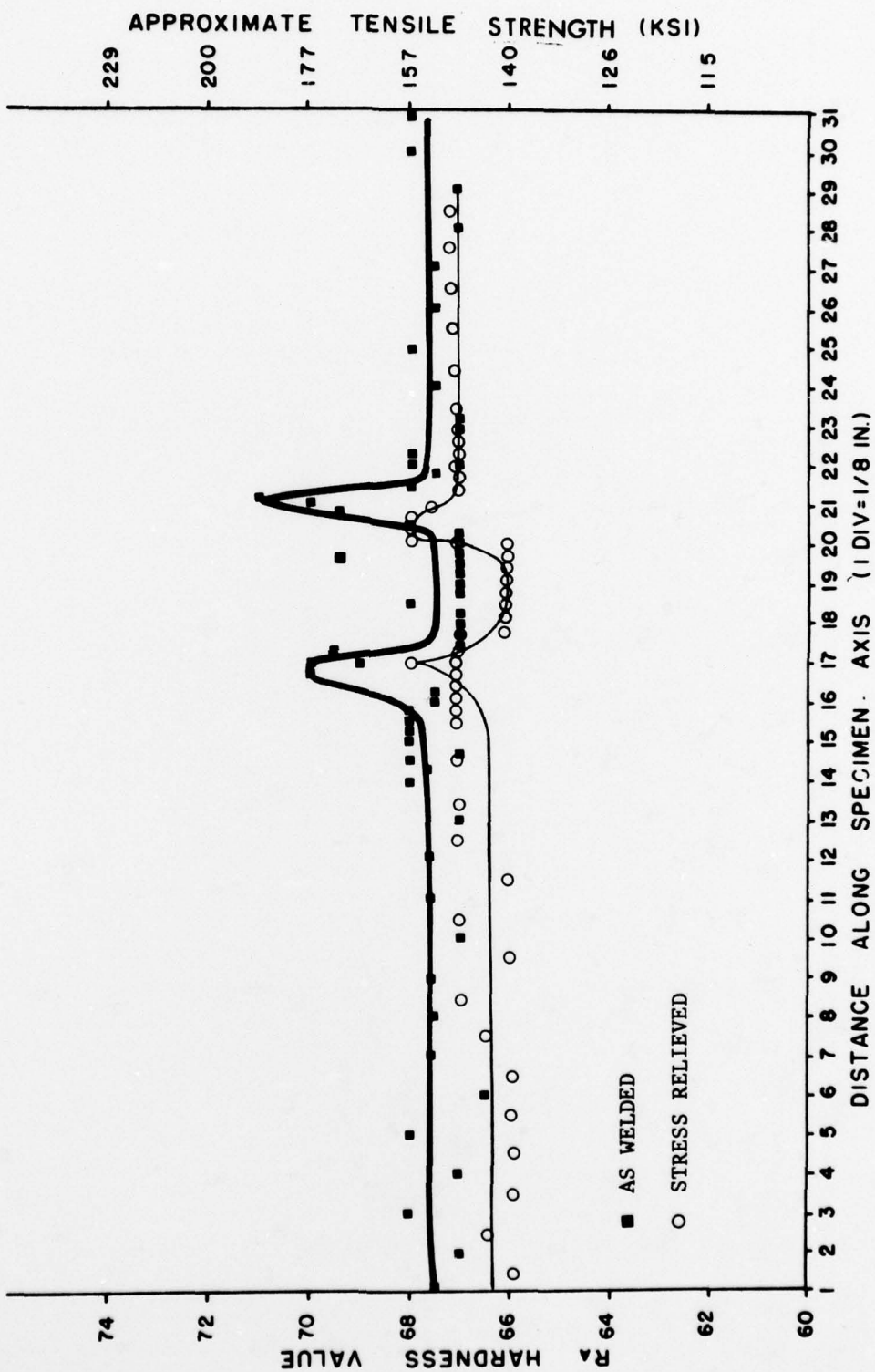


FIGURE 9: Hardness scan across Mig welded HY130 fatigue specimen from Series 3, before and after stress relief heat treatment.

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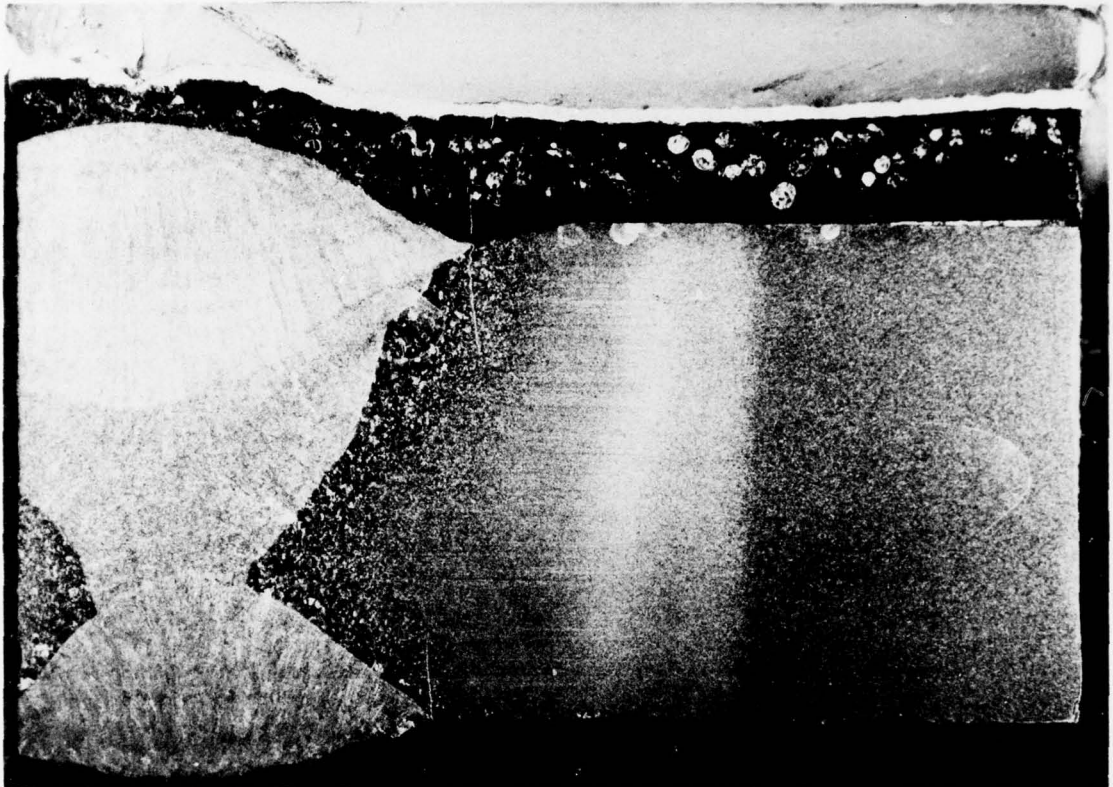


FIGURE 10: Section through HY130, E12018 welded, fatigue specimen from series 4, showing cracks initiating at edge of weld bead. (10x)

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FIGURE 11: Fatigue crack in HY130, E12018 welded, fatigue specimen (Series 4).



FIGURE 12: Electron micrograph of fatigue fracture face of AMVD plate specimen (9000x)



FIGURE 13: Electron micrograph of fatigue fracture face of AMVD HY130, E12018 weldment (9000x)

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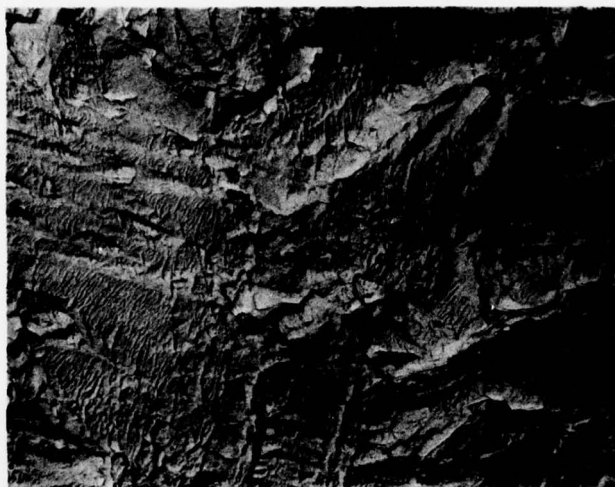


FIGURE 14: Electron micrograph of fatigue fracture in heat affected zone of HY130, E12018 weldment (at  $R = 0$ ) (9000x)



FIGURE 15: Electron micrograph of fatigue fracture in heat affected zone of HY130, E12018 weldment (at  $R = -1$ ) (9000x)

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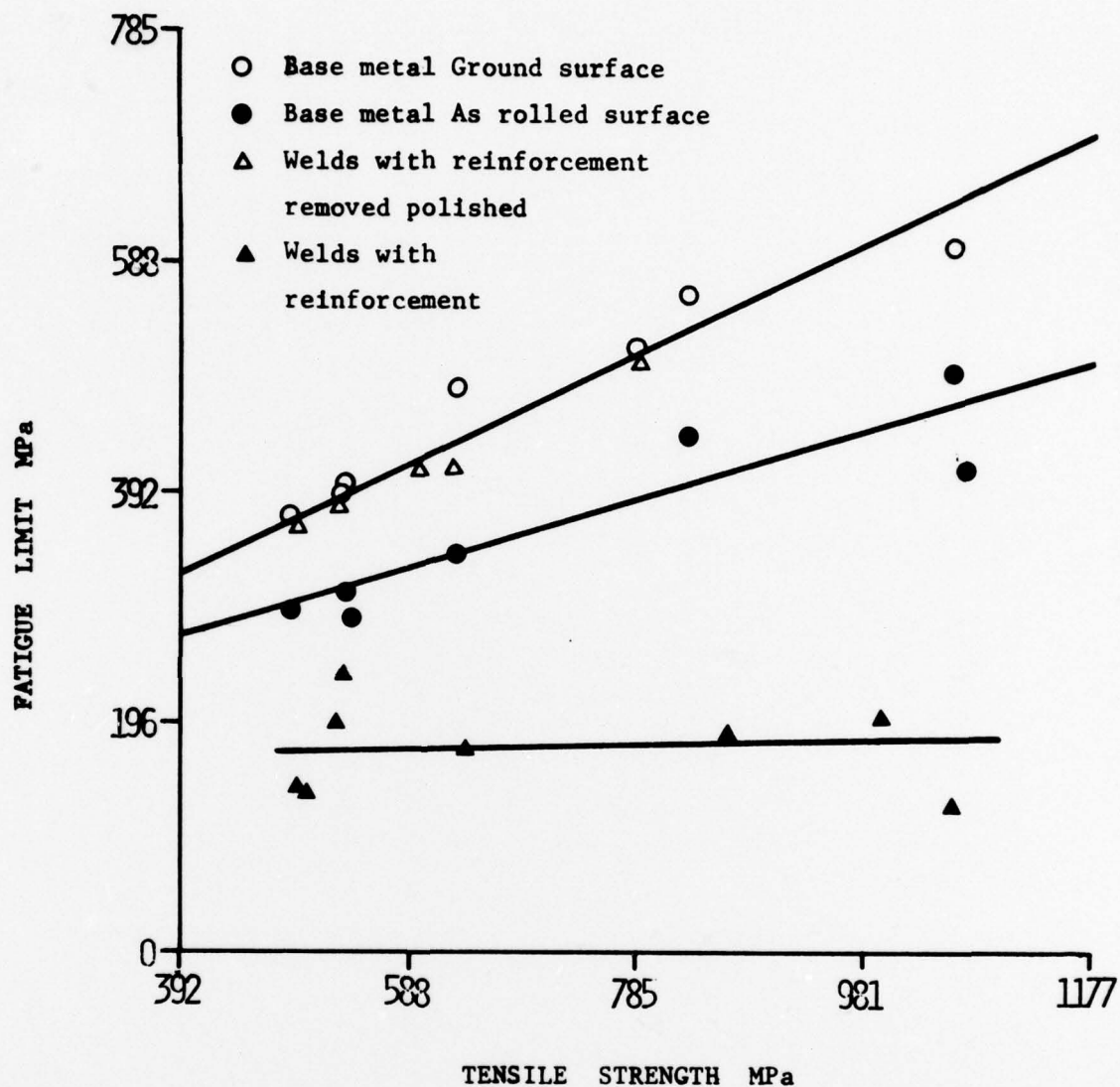


FIGURE 16: Graph showing range of fatigue properties with strength of high strength steels (from Takahashi et al<sup>14</sup>)

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